REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
15-01-2010	Conference Proceeding	

4. TITLE AND SUBTITLE
The Impact of the Number of Satellite Altimeters Used in a Data Assimilative Ocean Prediction System

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602435N

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
73-6207-09-5

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/PP/7320-09-9338

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

20100126146

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This paper describes the relative impact of the number of satellite altimeters used in the data assimilation portion of the U.S. Navy ocean prediction system. Using two different statistical and two different comparison methods, four different sets of results are evaluated. Much needed information is provided, regarding the ocean prediction accuracy that is achieved with satellite altimeters determined relative to in situ ocean observations.

15. SUBJECT TERMS
satellite altimeters, NLOM, MODAS, sea surface height

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL	8	Robert W. Helber
					19b. TELEPHONE NUMBER *(Include area code)* 228-688-5430

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

The impact of the number of satellite altimeters used in a data assimilative ocean prediction system

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***Abstract*-This paper describes the relative impact of the number of satellite altimeters used in the data assimilation portion of the U.S. Navy ocean prediction system. Using two different statistical and two different comparison methods, four different sets of results are evaluated. Much needed information is provided, regarding the ocean prediction accuracy that is achieved with satellite altimeters determined relative to in situ ocean observations.**

I. INTRODUCTION

During the years 2001 through 2003 there were three separate satellite altimeter data streams available providing global sea surface height (SSHA) measurements, 1) JASON-1, 2) ERS2/Envisat, and 3) the Geosat Follow-on (GFO). These systems provide a nearly real-time representation of ocean dynamical features and are the most important observation component of the U. S. Navy's operational global ocean prediction system. In light of their importance, it is surprising that estimates of the relative impact of the number of satellite altimeter data streams on ocean prediction systems are not readily available. To address this issue, a main goal of this analysis is to evaluate the relative prediction accuracy resulting from different numbers and configurations of altimeters providing data for the assimilation portion of the Navy's global ocean prediction system.

Satellite altimeter SSHA observations are particularly useful for mapping eddies, meandering currents, and fronts and are assimilated into the 1/32° Naval Research Laboratory (NRL) Layered Ocean Model (NLOM) [1]. NLOM transforms the along track data into high horizontal resolution (eddy resolving) SSHA fields that accurately represent the mesoscale variability. The NLOM SSHA fields are then used by the Modular Ocean Data Assimilation System (MODAS) to produce three-dimensional fields of temperature and salinity over the global ocean. Different versions of the MODAS output are produced from NLOM fields assimilating data from different sets ranging from zero to three altimeters. These predictions are then compared with in situ profile observations, which provide the ground truth estimates.

To evaluate the accuracy of the assimilation system relative to the in situ ocean observations, we employ two statistical methodologies. Both traditional Gaussian and non-parametric statistical methods are used to ensure that the results are not an artifact of the statistical methods. For similar reasons, two comparison frameworks are used. Comparisons are made point-for-point and in binned overlapping 1° radius regions 60 days long. The primary difference in the point-for-point and binned comparison frameworks is that the binning procedure evens the statistical weight of data that tend to vary geographically according to data density. By using binned data, or superposition-data, errors estimates in high and low density data regions have the same weight in global statistics. The metric for the comparisons is thermocline depth (*TD*), since the SSHA is most highly correlated with the thermocline [2]. We also asses the error geographically, revealing regions of the ocean where altimetry has a larger impact on the prediction accuracy than others.

The result of applying two statistical methodologies and two comparison frameworks is four ways to view the relative impact of the number of satellite altimeters used in an assimilative ocean prediction system. As a byproduct of this approach, the impact of the statistical and comparison methods is also revealed. In the end, you will see that satellite altimetry is an important component of ocean prediction even when considering the limitations of the assimilation system.

II. OBSERVATIONAL DATA

In situ ocean profiles of temperature and salinity from the World Ocean Database 2005 (WOD05), the U. S. Navy's Master Oceanographic Observation Data Set (MOODS), and Argo for the years 2001 through 2003 are combined. For the analysis we use only profiles that have at least temperature values, are of standard quality, have the shallowest depth level above 12 m and the deepest depth level below 150 m. An additional restriction is that in the upper 150 m no profile may have any gaps in depth levels exceeding 25 m. The resulting data set has 222,772 total profiles with 72,586 temperature (T) and salinity (S) profile pairs

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and 150,186 T only profiles. While the data is quality controlled, errors including profile location, XBT drop rate and other potential errors may still exist. To minimize the effect of noise in the observations, thermocline depth (*TD*), the approximate center of maximum temperature gradient below the mixed layer is used for the evaluation. Since TD is computed using a bulk gradient approach, it is insensitive to noise.

III. PREDICTION DATA

The satellite altimeter SSHA and SST data are directly assimilated into NLOM, an operational, globally eddy-resolving (1/32°), primitive equation 6 layered model with an imbedded bulk mixed layer [1]. A set of simulations using NLOM were run for years 2001-2003 differing only in the number of altimeter data streams assimilated, from 0 to 3. While NLOM has high horizontal resolution, the layered formulation means that the vertical structure is very coarse. To achieve better subsurface predictions we employ MODAS which estimates profiles of temperature and salinity from inputs of SST and/or SSHA using gridded polynomials at standard depths with coefficients determined by least squares fit to historical observations [3]. For this analysis, we input NLOM SSHA and SST into MODAS to produce synthetic profiles of temperature and salinity from which we compute the thermocline depth parameters at all the observation locations. By varying the number of satellite altimeter data streams used with NLOM, we have a suite of predictions for comparison with the observed profiles of temperature and salinity. Thermocline depth (TD) is computed from these predictions at the time and location of each of the observation profiles described in section II.

IV. COMPARISON AND STATISTICAL METHODS

Point-for-point comparisons are done by comparing the observations with the predictions interpolated to the location and time of the observations. Statistical error analyses are then applied to these matchups. A second comparison framework is where observation time and locations are grouped into analysis windows to produce superposition-data (super-data, hereafter). For this analysis the windows are overlapping 1° radius circular regions 60 days long computed each month for the entire analysis time period from Jan 2001 through December 2003. Super-data are defined as linear least-squares fits to the model or observation data within the analysis windows and represent the mean a_0 and temporal trend a_1. The fit parameters a_0 and a_1 are computed to produce the super-observations or super-predictions only for bins where the data spans at least 30 of 60 days. The super-data methods reduce the weight of individual data points in regions of the ocean with relatively high observation density. This is because the subsequent statistical analysis treats every super-data point the same. As a result, regions with a relatively large number of points have the same weight as regions will a small number of points. Both super-data and point-for-points results are discussed.

Traditional error analysis measure such as the mean bias (MB) and rms error (RMSE) assume Gaussian data distributions that generally do not apply in the ocean. Mean bias (MB) and RMSE, however, are well known and understood quantities. Fortunately there are non-parametric methods that do not make any assumptions about data distributions, which provide analogous measures of the mean and rms that are known in statistical parlance as location and scale, respectively. The non-parametric measures are theoretically preferable because they are more robust when applied to non-Gaussian data [4]. In this analysis both Gaussian and non-parametric statistical methods are used to test the robustness of the results.

V. RESULTS

The primary metric for this analysis is thermocline depth (TD), which is computed from both the MODAS synthetics and the observations. Summary diagrams [5] for all synthetics are presented in Figure 1 for both statistical methodologies and both comparison frameworks. In Figure 1 a and b the lowest error is closest to the upper left corner of the plot because there is a shallow TD bias (BM<0) and RMSE>0 for all synthetics. The statistical methods have the largest impact on the results as can be seen by comparing Figure 1 a and b. The results using Gaussian statistics have larger RMSE and standard error bars than for non-parametric statistics. Since Gaussian statistics assume normal data distributions, which are generally not valid in oceanographic data sets, outlier data points that violate the Gaussian data distribution assumption artificially inflate the error estimates. The comparison framework has a substantially smaller impact on the results. The only measurable difference is that RMSE is larger for the point-for-point comparison results (Figure 1a). The three altimeter case has the greatest accuracy, though not statistically different from the two altimeter case (Figure 1). The error is significantly improved with the inclusion of at least one satellite altimeter data stream and three altimeters are statistically different from one. The RMSE values are generally the same except for the zero-altimeter case, which has the least accuracy.

To explore the seasonal and regional error variability, consider a high SSHA variability region (HV) bounded by 20° to 50°N and 120°E to 160°W and a low SSHA variability region (LV) bounded by 0° to 20°N and 130°E to 150°W. In the HV region, the fit error *e* is larger when TD is deeper in the months of December, January, and March (compare solid lines of Figure 2, a and c). The % error, which is the percent of the error relative to the observed TD ($100\left[\left(a_0^{(A3)} - a_0^{(obs)}\right) / a_0^{(obs)}\right]$) is related to the rate of change fit parameter a_1. When the magnitude of a_1 is large the magnitude of the % error is also large (compare solid black lines of Figure 2, b and d). The % error tends to be negative because the synthetics have a shallow bias.

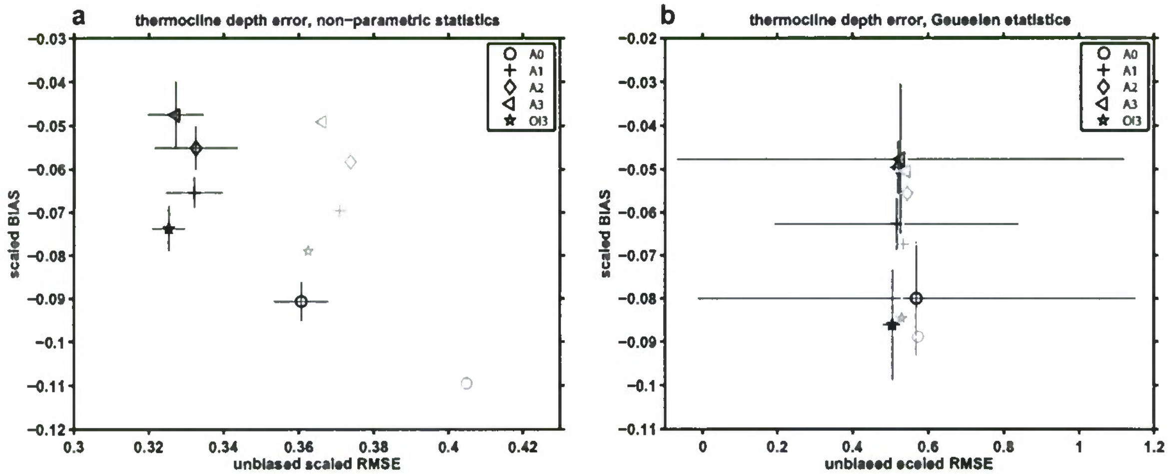

Figure 1. In (a) is the non-parametric statistics summary diagram [5] of RMSE (x-axis) and MB (y-axis) both scaled by the standard deviation of the observations. The black markers with 75% grey error bars represent super data comparisons while the 50% grey markers with the 25% grey error bars are for the point-for-point comparison framework. The error bars represent a 100 independent draw bootstrap standard error estimate. The markers in the legend indicate the number of satellite altimeter data streams that were assimilated where A0 represents no altimeters, A1 represents one altimeter, etc. The marker labeled OI3 is for three altimeters used in an optimal interpolation approach instead of NLOM. Panel (b) is the same but for Gaussian statistical methods and different axis limits.

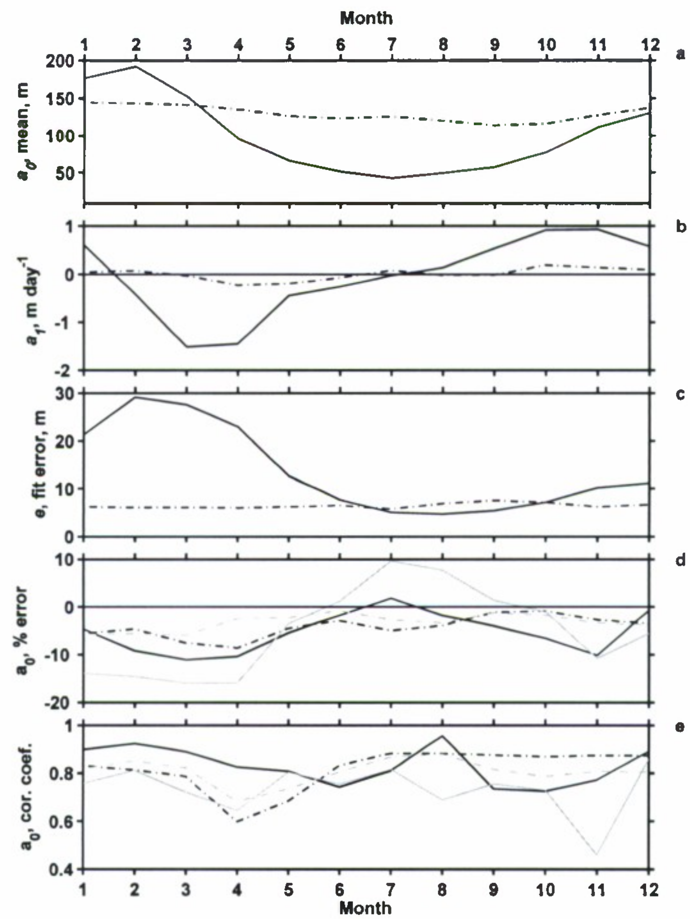

Figure 2. The median fit parameters (a) a_0, (b) a_1, (c) e, and the (d) percent error and (e) correlation of a_0 from A3 synthetics (in black) and climatology (in grey) by month, relative to the fit parameters determined directly from observations. The solid lines are for the HV region bounded by 20°N to 50°N and 120°E to 160°W, and the dashed-dot lines are for the LV region bounded by 0°N to 20°N and 130°E to 150°W in the northwest Pacific Ocean.

For the low variability region, represented by the dashed-dot lines in Figure 2, the effects of seasonality are relatively weak for a_0, a_1, and e, which change little throughout the year. In panels d and e of Figure 2, % error and correlation coefficient for both HV and HL regions are considered for both the three altimeter (A3) synthetics (in black) and climatology (in grey) cases. In Figure 2, d and e, the grey and black dashed dot lines are relatively close together as compared to the solid lines. This suggests that the A3 and climatology cases have similar errors in the LV region. In the HV regions, however, the CLIM case has larger magnitude in Figure 1d and lower correlation on average in Figure 1e. The average correlation coefficient in the HV region for a0 determined from the A3 synthetics is 0.93, higher than 0.83 for climatology. Average correlation is also relatively low in the LV region, 0.84 for both A3 and CLIM. In the LV region, the accuracy of the A3 synthetics is not significantly different from climatology. The value added by altimetry in the MODAS synthetics is evident only in the region of high SSH variability, where the signal stands out from the background noise.

VI. SUMMARY AND CONCLUSIONS

During the analysis time of this study (2001-2003) there were three satellite altimeter data streams available in near-real time for operational ocean prediction. Surprisingly, the relative accuracy of operational ocean predictions afforded by these data streams is not readily available. To address this issue, this paper investigates the relative prediction accuracy resulting from different numbers and configurations of altimeters providing data for the assimilation portion of the Navy's global ocean prediction system.

The general results show that accuracy provided by the satellite altimeter data streams is greater in regions of high SSHA variability, and significant error reduction is achieved with the addition of at least one satellite altimeter data stream. Additional error reduction when assimilating data from three altimeters versus one is significant only in bias. These conclusions are drawn from both the point-for-point and super-data frameworks when using non-parametric statistical methods. The lack of significant skill improvement between two and three satellite altimeter data sets may be a consequence of the length and time scales associated with the NLOM assimilation and the smoothing associated with gridded climatological coefficients of MODAS. As a result, this system is unable to take full advantage of the added spatial detail provided by multiple altimeters. The simulated error experiment of Smedtad et al. [6] also indicates that the marginal reduction in SSHA error decreases for each additional satellite data stream.

The statistical methodologies are found to have a relatively large impact on the results. Evaluation based on traditional statistics that assume Gaussian data distributions result in inflated error and error uncertainty estimates. Using non-parametric statistics circumvents the need for strict and often unfounded assumptions about the data distribution. The two comparison frameworks used in this analysis have a lesser impact. The effect of the super-data methods is to even the influence of data between low and high density observation regions. Since the global error results for the point-for-point framework are slightly larger than for the super-data framework, high density observation regions tend to occur in areas with larger errors.

Comparing predictions to in situ observations is the ultimate test in that the observations are the closest information we have to the true ocean condition. This type of comparison, however, is inherently plagued with representation errors because the observations generally have more physical processes influencing the measurements on shorter space and time scales than the predictions are able to resolve.

ACKNOWLEDGMENT

This publication is a contribution to the Assessing UUV Sampling Strategies with Observation System Simulation Experiments project supported by the Office of Naval Research under program element 602345N. We also thank Jan Dastugue for skillful rendering of figures.

REFERENCES

[1] J. F. Shriver, H. E. Hurlburt, O. M. Smedstad, A. J. Wallcraft, and R. C. Rhodes, "1/32° real-time global ocean prediction and value-added over 1/16° resolution," *J. Mar. Sys.*, vol. 65, pp. 3-26, 2007.

[2] H. E. Hurlburt, "Dynamic transfer of simulated altimeter data into subsurface information by a numerical model," *J. Geophys. Res.*, vol. 91, pp. 2372-2400, 1986.

[3] D. N. Fox, W. J. Teague, C. N. Barron, M. R. Carnes, and C. M. Lee, "The Modular Ocean Data Assimilation System (MODAS)," *J. Atmos. Ocean. Tech.*, vol. 19, pp. 240-252, 2002.

[4] J. R. Lanzante, "Resistant, robust and non-parametric techniques for the analysis of climate data: Theory and examples, including applications to historical radiosonde station data," *Inter. J. Climatology*, vol. 16, pp. 1197-1226, 1996.

[5] J. K. Jolliff, J. C. Kindle, I. Shulman, B. Penta, M. A. M. Friedrichs, R. Helber, R. A. Arnone, "Summary diagrams for coupled hydrodynamic-ecosystem model skill assessment," *J. Mar. Sys.*, vol. 76, doi: 10.1016/j.jmarsys.2008.05.014, 2009.

[6] O. M. Smedstad, H. E. Hurlburt, E. J. Metzger, R. C. Rhodes, J. F. Shriver, A. J. Wallcraft, and A. B. Kara, "An operational eddy resolving 1/16°global ocean nowcast/forecast system," *J. Mar. Sys.*, vol. 40, pp. 341-361, 2003.